THz RADIATION SOURCE THROUGH PERIODICALLY MODULATED STRUCTURES

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13. ABSTRACT *(Maximum 200 words)*

While the previous period was dedicated to the study of combinations of different superlattices using an advanced technique of hot electron spectroscopy, we have concentrated our activities in the 5th period of this project on the study of quantum wires. We could demonstrate for the first time that the magnetophonon effect can be used to characterize quantum wires with a very low number of subbands occupied. In this case the Shubnikov-deHaas technique cannot be applied any more. The development of this technique is an important step forward in the realisation of high quality quantum wires. High quality wires with 1 to 3 meV subband splittings were produced. These quantum wires with subband splittings in the THz region are one possible candidate for a coherent source in this frequency range. Future work will concentrate on new methods to produce quantum wires with tunable subband spacings. Novel side gate structures are under investigation at present together with V-groove overgrowth techniques. We hope to achieve subband spacings close to 10 meV tunable over a wide range.

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Characterization of Quantum Wires

Introduction

Arrays of quasi one dimensional electron channels (quantum wires) have possible future applications as narrow band, electrically tunable detectors of far infrared (FIR) radiation. Fig. 1 is a plot of the photoconductivity signal of an array of nanowires and shows the potential of this system for detector applications. The most interesting feature of the photoconductivity peaks shown in Fig. 1 is their spectral sharpness which is of the order of one wavenumber. The lateral quantization of the electron states into 1D subbands with a characteristic energy difference E_0 of 1 - 10 meV implies the suitability of these systems as a detection device for FIR radiation, if it becomes possible to find a way of tuning the energetic subband spacing and thus to increase the spectral range of the Q1D detecting system. There are several methods to achieve this tuning of the subband spacing. For example, the variation of the electron density in the wires is found to cause an increase in E_0.

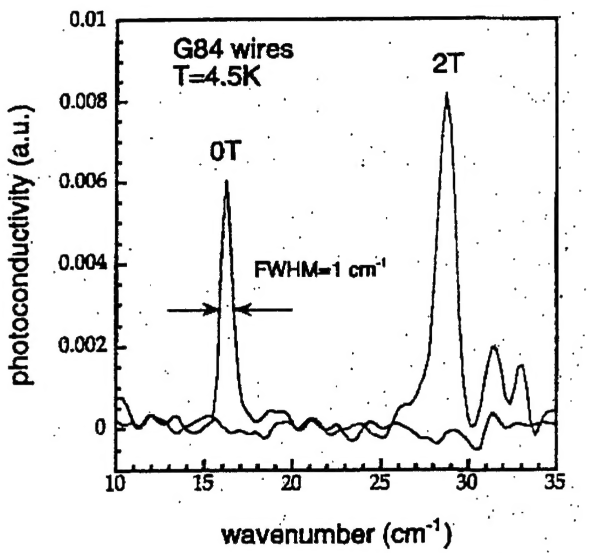

Fig. 1 Photoconductivity signal of an array of quantum wires.

For the spectral sharpness of all features connected with the energy spectrum of the confined electrons, as the photoconductivity peaks shown in Fig.1, it is necessary to reduce the influence of impurity scattering on the level broadening of the 1D subbands. In this context the most interesting systems are heterostructures at low doping and thus low electron concentrations in the conducting channel.

Low electron concentration, on the other hand, implies that only low numbers of subbands are occupied in the Q1D channels. Since in this case standard transport characterization methods of wires, like magnetic depopulation measurements, rely on the fact that sufficient numbers of subbands are occupied in order to extract E_0, the latter features require new ways for the transport characterization which are also suitable for low density systems. One possibility is to exploit the magnetophonon effect in 1D systems

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which has long been predicted theoretically and which is, due to the special situation for quantum wires, a useful tool for the characterization of subband energies in these systems.

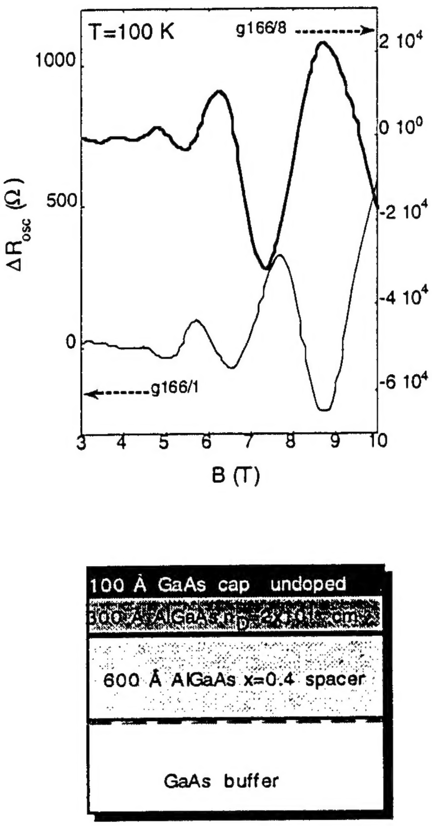

Fig.2: Oscillatory part of the high temperature magnetoconductivity for two different samples g166. Bottom: sample structure of g166.

Results

The structure of the conventional modulation doped heterostructures used in this work and referred to as g166 is shown in Fig. 2. The electron mobility and electron density of the unstructured sample are 1.6 x10^6 cm^2/Vs and 1.1 x10^{11} cm^{-2}, respectively, at 4.2 K. The only special feature of this sample structure is the low doping concentration which allows to get appreciable lateral confinement of the electrons when only very shallow etching is done.

In the case of weakly confined electrons the high temperature magnetoresistance ρ_{xx} is expected to have a component ρ_{osc} which has the form of an oscillatory function damped exponentially with decreasing magnetic field. Since the measurements reported in this paper were restricted to a magnetic field range extending to a maximal field strength of 10 T it is necessary to obtain good resolution of the magnetophonon oscillatiory structure in ρ_{xx} at fairly low magnetic fields. Thus, if quantum wires are fabricated using the shallow etching method, one has to take into account the considerable surface roughness scattering acting on the confined electrons which is induced by the etching process. Indeed, a strong dependence of the relative amplitude and resolution of MPR on sample structure and preparation parameters is found. The magnetophonon effect in Q1DEGs is found to be very well resolved at low magnetic fields for those samples where impurity scattering is reduced as far as possible by e.g. large spacer layers and low doping. The latter sample property also keeps the influence of surface roughness scattering within tolerable limits since appreciable lateral confinement can be obtained in these cases by very shallow etching.

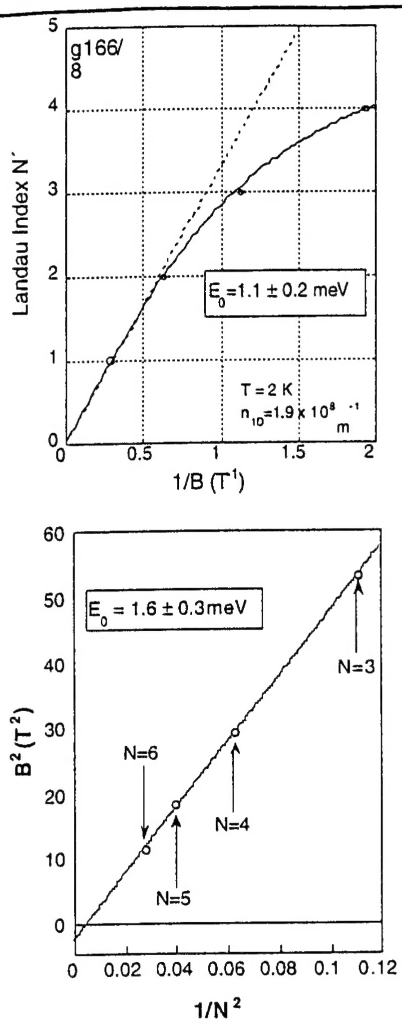

Fig.3 top: Landau plot of a magnetic depopulation measurement on g166/8. bottom: squared magnetic field position of the resonant minima in Fig.2 vs N^2 for the same sample

The experimentally observed influence of sample structure and etching depth on the amplitude and resolution of the magnetophonon oscillations is summarized in Fig. 2 which shows the oscillatory part of the magnetoresistance ΔR_{osc}, obtained from the magnetoresistance traces measured at temperatures around 100 K after subtraction of the background resistance for two different samples of the type g166, g166/1 being slightly more deeply etched than g166/8. Deeper etching is thus found to reduce the amplitude of the magnetoresistance oscillations by almost an order of magnitude (note the different y-axis scales in the plots). Thus, to observe sufficiently pronounced MPRs we had to limit our investigations to the case of relatively weak confinement, i.e. wires displaying subband energy differences in the range of 1meV, and fairly low electron densities.

The main purpose of this work was to verify that the magnetophonon effect can be used as a tool for the characterization of Q1DEGs, i.e. for the determination of subband energies of quantum wires with small numbers of subbands occupied. We therefore compare in Fig. 3 the results of a high temperature measurement with those of a magnetic depopulation measurement performed on a sample of the type g166 at 2K. The electron density has been adjusted using the procedure described in the previous subsection. Fig. 3a) shows a Landau plot obtained from a MD experiment for a particular electron density. The sublevel index N´ is plotted versus the inverse magnetic field position of the MD minima in the magnetoresistance traces recorded at T = 2 K. The deviation of the plot from a straight line shows clearly the 1D behavior of the energy spectrum of the laterally confined electrons. The solid line stems from a fit to the data according to the model of Berggren et al.[1] assuming a parabolic confinement potential, yielding a subband spacing of 1.1 ± 0.2 meV.

In Fig.3 b) we plot the squared magnetic field positions of the resonant minima in the oscillatory part of R_{xx} (cf. Fig.2) measured at T=100K versus the inverse squared index N which is defined according to the generalized resonance condition[2] $N\,\hbar\omega_{eff} = E_{LO}$, with E_{LO}=36.6 meV being the LO phonon energy in bulk GaAs. If one assumes parabolic

REPORT DOCUMENTATION PAGE (SF298)
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confinement, $\hbar\omega_{eff}$ is given by $(\hbar\omega_{eff})^2 = (\hbar\omega_{cyclotron})^2 + E_0^2$, E_0 being the subband spacing of the 1D wires. Using this expression, the resonance condition can be rewritten in the following form :

$$B^2 = \left(\frac{m^*_{Pol}}{e\hbar}\right)^2 \frac{E_{LO}^2}{N^2} - \left(\frac{m^*_{Pol}}{e\hbar}\right)^2 E_o^2.$$

According to this formula, the B^2 values plotted versus $1/N^2$ should give a straight line whose slope is a measure of the polaron effective mass in the quantum wire, whereas its intersection with the B^2-axis can be used for the determination of the subband spacing E_0. It should be emphasized that this simple relationship is only valid if the confining potential can be approximated by a parabolic well. As can be seen from Fig. 3b) the linearity of the experimental relationship between B^2 and $1/N^2$ is fulfilled very well indicating that the assumption of a parabolic confinement potential should be a good approximation. In another major approximation made in the analysis we take for the LO phonon energy the value for bulk GaAs neglecting any influence of the lateral confinement on E_{LO}. With these assumptions we obtain from the data shown in Fig.3 b) a magnetophonon effective mass of 0.069 m_e and a subband spacing of 1.6±0.3 meV. The latter is enhanced in comparison to the corresponding value obtained from a subsequent magnetic depopulation experiment (1.1 ± 0.2 meV, Fig. 3a). This enhancement was found in all investigated samples where a direct comparison was feasible and the subband spacings determined from MPR lie some 30 - 50% above those extracted from magnetic depopulation experiments. This difference can be easily explained in terms of the potential form underlying the investigated shallow etched quantum wires[3]

Having shown that MPR are indeed a useful tool for the determination of sublevel spacings in Q1DEGs one may use the method for a systematic study of the dependence of E_0 on the electron density by employing the procedure described in the experimental part of this paper. This allows to extend the investigation to regions where the electron density is so low that the relevant information could not be obtained from MD experiments alone.

Fig. 4 shows the subband spacing E_0 as a function of the 1D electron density for sample g166/1 and g166/8. The open circles result from an analysis of the MPR measurements at T = 100 K, solid circles show the results of magnetic depopulation experiments performed at T = 2 K. The latter could be obtained only in those cases where a sufficient number of subbands was occupied to apply the evaluation method proposed by Berggren et al.[1] .

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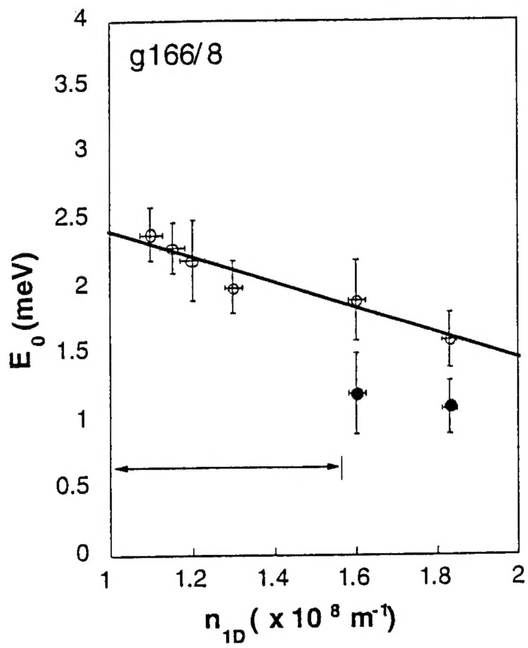

Fig. 4: Subband spacing obtained from magnetophonon analysis (open circles) and magnetic depopulation experiments (solid circles) for g166/8

The solid line drawn in Fig. 4 stems from a linear fit to the data and is only intended as a guideline to the eye. To get an independent estimate of the corresponding electron densities one may resort to eq. (8) of ref. 1 which asserts that the high field values in the N vs 1/B-(Landau-)plot should lie on a straight line having a slope proportional to $(n_{1D} E_0)^{2/3}$. The corresponding values for the one dimensional electron densities are extracted by exploiting this linearity of the N(1/B)-plot, taking for the subband spacing E_0 the values obtained from the MPR data. The observed increase of the subband spacing with decreasing electron density is easily interpreted in terms of a reduction of the screening of the bare confining potential. The same effect is observed also for samples with a different structure and using other methods for the variation of the electron density, e.g. by applying a backgate voltage and using only MD experiments for the determination of E_0.

Future work

Having thus demonstrated the magnetophonon effect to be a transport characterization method particularly suitable for the analysis of low density 1D systems, future work will have to concentrate on alternative methods for the tuning of the subband spacing in wires. These alternatives must yield tuning effects of the lateral confinement in a more controllable way. Of particular interest are novel side gated structures which not only provide the desired tuning effects but also give access to higher subband energies[4] (10 meV sublevel spacing demonstrated so far).

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